

ARMY RESEARCH LABORATORY



**User Manual for the Microsoft Window Edition of the
Simple Acoustic Decision Aid (WSADA) Version 1.3**

John M. Noble

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March 2003

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Army Research Laboratory

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by John M. Noble
Computational and Information Sciences Directorate

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Chapter 1

Introduction

With the increased computational power available to battlefield sensors today, it is very possible to develop algorithms to make sensors and sensor nodes "aware" of the environmental impacts on their performance. The limiting factor on the performance of these algorithms is the availability of atmospheric data to perform the calculations. With the increase in the number of environmental sensors on a platform and the networking of sensors, the full impact of the environment on sensor performance will be determined in the battlefield either by the sensor or communicated to the sensor by computers higher up the chain. This report describes a very basic model that can be used by current sensor platforms to calculate limited information about the environmental impact on its performance.

One of the early propagation models used rays to trace the propagation of sound through the atmosphere. A ray model is very simple and not very computer intensive. This type of model will account for the refraction of sound by the atmosphere and the attenuation due to molecular absorption. But typically raytrace models do not account for diffraction, scattering, and complex ground impedance. A hybrid raytrace model was developed in the mid-80s by the University of Mississippi [2], which used

a raytrace model to determine the path lengths of direct and reflected rays in the atmosphere. This was coupled with a spherical wave model using the path lengths of the direct and reflected rays in the formulation allowing for the incorporation of complex ground impedance. This is the type of model used for this development.

The other key to this simple model is a routine to compute an atmospheric profile for the ray model to use. The algorithm used is based on similarity theory with an energy balance model to initialize the similarity model. The energy balance model allows for very basic atmospheric information to be used to generate an atmospheric profile. The drawback to this method is the vertical height limitation of the calculated profile. Similarity theory is based in the surface layer of the atmosphere or the first 100-200 m of the atmosphere. Due to this, the profile generated is only high enough to drive the acoustic propagation model out to 3-5 km in range. As networked sensors become more abundant in the battlefield, it will eventually become possible to download an atmospheric profile for the region where the sensor is located. When this becomes possible, then the performance prediction range will increase.

Chapter 2

Propagation Theory

2.1 Speed of Sound

Meteorological phenomena can have a significant effect on the received sound field. Some of the meteorological variables affecting the speed of sound in air are pressure, temperature, wind velocity, and humidity. To observe the effect of each meteorological variable, consider each one independently and examine the equation for the speed of sound in air. The value c , according to Laplace's adiabatic assumption for air as an ideal gas, [3] is

$$c(T) = \sqrt{\frac{\gamma RT}{M}} \quad (2.1)$$

where γ is the ratio of specific heats, R is the universal gas constant equal to 8314.16 J/(kg K), and M is the molecular weight of air.

The presence of water molecules alters the sound speed by lower γ and decreasing M . The decreased M dominates so that the overall effect of increasing humidity is an increasing sound speed. These changes can be quantified as

$$\gamma = \frac{7+h}{5+h} \quad (2.2)$$

and

$$M = 29 - 11h \quad (2.3)$$

where h is the fraction of water molecules in air. As the amount of water in the atmosphere increases, the molecular weight of a parcel of air will decrease since the molecular weight of a water molecule is less than both diatomic nitrogen and diatomic oxygen. As a result the sound speed increases as the fraction of water molecules in the air increases. In order to calculate the fraction of water molecules in air, the *Goff-Gratch* equation [3] must be used to first calculate the partial pressure of saturated water vapor, P_{sat} at temperature T . This equation is

$$\begin{aligned} \log_{10} \left(\frac{P_{sat}}{P_o} \right) &= 10.79586 \left[1 - \left(\frac{T_{01}}{T} \right) \right] - 5.02808 \log_{10} \left(\frac{T}{T_{01}} \right) \\ &+ 1.50474 \times 10^{-4} \left(1 - 10^{-8.29692[(T/T_{01})-1]} \right) \\ &+ 0.42873 \times 10^{-3} \left(10^{4.76955[1-(T_{01}/T)]} - 1 \right) - 2.2195983 \end{aligned} \quad (2.4)$$

where $T_{01} = 273.16$ K and $p_o = 1$ atm or the reference pressure.

After the value for P_{sat} is determined, the fraction of water molecules in air can be calculated using the following relationship:

$$h = \frac{10^{-2}(RH)P_{sat}}{P} \quad (2.5)$$

where RH is the relative humidity in percent and P is the pressure in atmospheres.

The magnitude of the dependence of the sound speed on humidity is not obvious. To understand the degree of the effect of humidity on sound speed, consider a particular case. At 20° C, the difference in sound speed between 0 and 100 percent humidity is 2 m/s. A fluctuation in the humidity of this amount is very unlikely. If the variation

in humidity is reduced to a change of 50 to 100 percent, the change in the sound speed is only 1 m/s. Therefore, the variation of sound speed caused by changes in humidity should always be much less than 1 m/s. Generally, humidity fluctuations can be ignored.

The effect of the wind speed on the speed of sound is a vector relation. The effective sound speed is calculated using

$$c_{\text{eff}} = c(T) + u \cdot \cos(\theta_w - \pi - \theta_R) \quad (2.6)$$

where $c(T)$ is the speed of sound in the absence of wind at temperature T , u is the magnitude of the horizontal wind speed, θ_R is the bearing of the receiver from the source, θ_w is the direction from which the wind blows, and $\theta_w - \pi$ is the direction the wind is blowing (figure 2.1). All directions are relative to north.

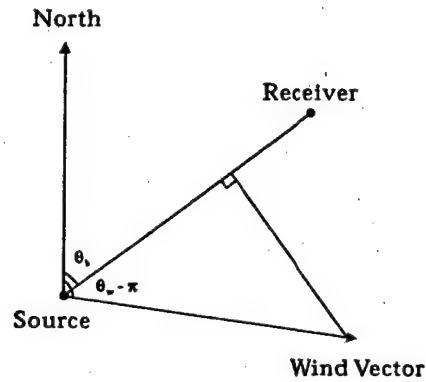


Figure 2.1: Diagram of Geometry Definition

The sound speed will also vary with height because the sound speed is a function of temperature and vector wind speed. This variation will cause the acoustic wave to be refracted as it propagates through the atmosphere. The degree of refraction the wave undergoes is related to the sound speed gradient present in the atmosphere. If the sound speed increases with height, the acoustic wave will be refracted downwards. If

the sound speed decreases with height, the acoustic wave will be refracted upwards.

2.2 Ray Theory

In a horizontally stratified atmosphere, the ray path traversing a layer with a constant sound speed gradient forms an arc of a circle [4]. The launch angles, θ_s for the ray paths are related by Snell's law,

$$\frac{\cos \theta(z)}{c(z)} = p = \frac{\cos \theta_s}{c_s} \quad (2.7)$$

where c_s is the sound speed at the source and z is the height above the ground. Applying equation 2.7 to a constant sound speed gradient g yields

$$\cos \theta = c(z)p = [c_i + (z - z_i)g]p. \quad (2.8)$$

Therefore,

$$z = R \cos \theta + z_o \quad (2.9)$$

where $R = |1/pg|$ is the radius of the circular arc defining the ray path and $z_o = z_i - c_i/g$ is the center of the circular arc. From these equations, the range traversed with within the layer can be calculated using

$$\Delta r = R |\sin \theta_f - \sin \theta_i| \quad (2.10)$$

and the layer penetration depth can be calculated by

$$h = R |\cos \theta_f - \cos \theta_i| \quad (2.11)$$

where θ_f and θ_i are the final and initial ray angles within the layer, respectively. The

arc length of a ray transversing a layer can be calculated using

$$\Delta \ell = R | \sin^{-1}(\sin \theta_f \cos \theta_i - \cos \theta_f \sin \theta_i) | \quad (2.12)$$

and for a ray vertexing within a layer, the equation reduces to

$$\Delta \ell = R | \theta_i | . \quad (2.13)$$

These steps form an iterative process to propagate a ray through a horizontally stratified atmosphere. The problem is determining the proper value for θ_s to propagate a ray from the source to the receiver. This is accomplished by fanning rays through an angular segment and determining if a pair of rays "brackets" the receiver. If the program finds a pair of rays that bracket the receiver, the program iteratively narrows down to the correct ray that propagates from the source to the receiver.

2.3 Absorption of Sound by the Atmosphere

Viscosity, heat conduction, and molecular exchanges of energy basically cause losses in the medium. In the nineteenth century, the mechanisms of viscosity and heat conduction were the only ones suspected of causing dissipation of sound. Therefore, they are presently referred to as classical absorption.

In classical absorption, if one represents the effect of absorption by a factor $e^{-\alpha r}$ where r is the distance of propagation, then the attenuation coefficient α_{cl} due to viscosity and heat conduction is given by equation (17) from *Physical Acoustics XVII* [5]:

$$\alpha_{cl} = 5.578 \times 10^{-9} \frac{T/T_o}{T + 110.4} \frac{f^2}{P/P_o} \quad (2.14)$$

The units of α_{cl} in equation (24) are nepers/meter, where P_o is the reference pressure of $1.01325 \times 10^5 \text{ N/m}^2$ (1 atm), P is pressure in N/m^2 , T_o is the reference temperature

of 293.15K, T is the temperature in Kelvin, and f is the frequency in hertz.

In molecular absorption, energy exchanges at the molecular level include rotational and vibrational modes. Analysis of the rotational mode shows that its representative attenuation coefficient is proportional to α_{cl} , the classical attenuation coefficient:

$$\frac{\alpha_{rot}}{\alpha_{cl}} = 4.16e^{-16.8T^{-1/3}} \quad (2.15)$$

when $293^\circ K < T < 690^\circ K$.

For frequencies below 10 MHz, it has been demonstrated that energy losses due to classical and molecular absorption are additive. A simplified empirical form of the equation can be written

$$\alpha_{cr} = 1.83 \times 10^{-11} \frac{\sqrt{T/T_0} f^2}{P/P_0}, \quad (2.16)$$

which is correct within 2 percent for $213 < T < 373K$.

The vibrational mode of absorption should also be considered. Because the atmosphere is composed mostly of nitrogen and oxygen, each will contribute an attenuation coefficient. The vibration absorption is given by

$$\alpha_{vib,j} = \frac{4pX_j}{35c} \left(\frac{q_j}{T} \right)^2 \frac{e^{-q_j/(Tf^2)}}{f_{r,j} + (f^2/f_{r,j})} \quad (2.17)$$

where j stands for either oxygen or nitrogen, X_j is the mole fraction of air component considered (0.20948 for oxygen and 0.78084 for nitrogen), q_j is the characteristic vibrational temperature (2239.1K for oxygen and 3352.0K for nitrogen), and c is the speed of sound at temperature T in m/s. The $f_{r,j}$ are the individual relaxation frequencies for oxygen and nitrogen. Computation of these depends on the relative humidity and atmospheric pressure. The relaxation frequencies are given by:

$$f_{r,O} = \frac{P}{P_o} \left(24 + 4.04 \times 10^4 h \frac{0.02 + h}{0.391 + h} \right) \quad (2.18)$$

$$f_{r,N} = \frac{P}{P_o} \sqrt{\frac{T_o}{T}} \left(9 + 280 h e^{-4.170(T_o/T)^{1/3} - 1} \right)$$

The total attenuation coefficient is then the sum of α_{cr} and $\alpha_{vib,j}$. Figure 2.2 is a log-log plot of total attenuation coefficient of $T = 20^\circ\text{C}$ and $Rh = 20$ percent, adapted from Ref 5. It shows the contributions to attenuation from classical absorption, vibrational relaxation of Nitrogen and Oxygen, and the total attenuation coefficient due to the sum of these three attenuation mechanisms.

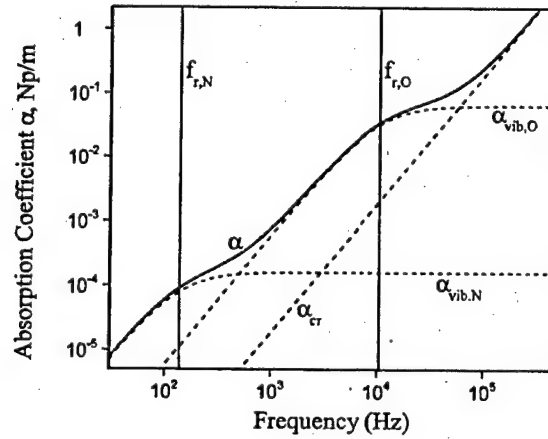


Figure 2.2: Log-log plot of sound absorption coefficient versus frequency for sound in air at 20°C at 1 atm pressure and with a water vapor fraction h of 4.676×10^{-3} ($Rh = 20\%$).

The attenuation coefficient α is roughly proportional to the square of the frequency. Hence, when frequency doubles, attenuation will quadruple. The attenuation of the sound wave due to molecular and vibrational absorption is very important for frequen-

cies over 250 Hz. For frequencies below 250 Hz, this attenuation does not contribute much to the total attenuation of the sound wave.

2.4 Complex Ground Impedance

There are several models available for calculating the complex ground impedance. The impedance model used in WSADA is the Four Parameter Model of Attenborough [6]. In this impedance model, the complex normalized characteristic impedance of the ground is calculated using

$$Z_c \cong \frac{\left[\frac{4q^2}{3\Omega} + i \frac{S_f^2 \sigma}{\omega \rho_o} \right]}{k_b} \quad (2.19)$$

where $q^2 = \Omega^{-n'}$, S_f is the pore shape factor ratio, Ω is the porosity of the ground, σ is the flow resistivity of the ground (mks) rayls, ω is the angular frequency ($2\pi f$), ρ_o is the density of air ($1.2 \times kg/m^3$), and k_b is the normalized wave number. The normalized wave number is computed from

$$k_b \cong \sqrt{\gamma \Omega} \left[\left(\frac{4}{3} - \frac{\gamma - 1}{\gamma} N_{pr} \right) \frac{q^2}{\Omega} + i \frac{S_f^2 \sigma}{\omega \rho_o} \right]^{1/2} \quad (2.20)$$

where γ is the ratio of specific heats, equation (2), and N_{pr} is the Prandtl number (0.724).

The parameters S_f , Ω , σ , and n' are normally varied until agreement is reached between impedance measurements and the impedance model is achieved. However, this method of determining the four parameters cannot always be completed if time or resources is lacking. To aid the user when the four parameters are unknown, there are a series of general descriptions of a variety of ground surfaces to chose from. The user has the option to enter the values for the four parameters, if known.

Some ground surfaces have a layered structure that results from the gradual depo-

sition of material over a soil base. Some examples are a layer of snow over frozen ground, decomposition of organic material over clay or sandy soil, or a well plowed pasture over clay or harder packed soil. An effective impedance $Z(d)$ can be calculated for a semi-infinite layer of impedance Z_2 covered by a layer, depth d , or another material of impedance Z_1 . The effective impedance is given by

$$Z(d) = \left[\frac{Z_2 - iZ_1 \tan(k_b d)}{Z_1 - iZ_2 \tan(k_b d)} \right] Z_1 \quad (2.21)$$

where k_b is the bulk propagation constant in the top layer of the ground. The parameters Z_1 , Z_2 , and k_b are calculated using equations (30) and (31) from Attenborough's Four Parameter impedance model. In WSADA, the complex ground impedance is handled by the graphical users interface.

2.5 Hybrid Propagation Model

WSADA uses a combined ray theory and spherical wave propagation model. Ray theory does not account for the complex interaction of the acoustic wave with the ground and the spherical wave model does not account for the refraction of the acoustic wave as it propagates through the atmosphere. The ray theory portion of the model was described in section 2.2. The total acoustic field can be expressed as

$$\phi_{TOT} = \frac{e^{(ik_1 - \alpha_1)R_1}}{R_1} + \frac{e^{(ik_1 - \alpha_2)R_2}}{R_2} \{R(\theta_o) + B[1 - R(\theta_o)]F(w)\} \quad (2.22)$$

where k_1 is the propagation constant for air, R_1 is the direct distance from source to receiver, R_2 is the path length from source to receiver that includes one ground reflection, α_1 and α_2 are the molecular absorption coefficients for the direct and reflected paths, $R(\theta_o)$ is the plane-wave reflection coefficient, B extends the local reaction to extended reaction, and $F(w)$ is the 'sphericity' factor. The terms in the braces are the

reflection coefficient for a complex impedance surface that accounts for spherical wave reflections.

The plane-wave coefficient is given by

$$R(\theta_o) = \frac{\cos \theta_o - M(n^2 - \sin^2 \theta_o)^{1/2}}{\cos \theta_o + M(n^2 - \sin^2 \theta_o)^{1/2}} \quad (2.23)$$

where θ_o is the angle of incidence of the incoming wave with the ground measured from the vertical, $n = k_2/k_1$ with k_2 being the propagation constant in the ground, and M is derived from the relationship $\beta_c = Mn = 1/Z_c$ with β_c and Z_c being the normalized characteristic admittance and impedance, respectively. The term B is determined using

$$B = \left\{ \frac{[\cos \theta_o + (1 - n^{-2} \sin^2 \theta_o)^{1/2}](1 - n^{-2})^{1/2}}{[\cos \theta_o + \beta_c(1 - n^{-2})^{1/2}(1 - M^{-2})^{-1/2}](1 - n^{-2} \sin^2 \theta_o)^{1/2}} \right\} \quad (2.24)$$

$$\left\{ \frac{[(1 - M^{-2})^{1/2} + \beta_c(1 - n^{-2})^{1/2} \cos \theta_o + (1 - \beta_c^2) \sin \theta_o]^{1/2}}{(1 - M^{-2})^{3/2}(2 \sin \theta_o)^{1/2}(1 - \beta_c^2)^{1/4}} \right\}$$

The 'sphericity' factor is given by

$$F(w) = 1 + i\sqrt{\pi}we^{-w^2} \operatorname{erfc}(-iw), \quad (2.25)$$

where w is the "numerical distance" given by

$$w^2 = ik_1 R_2 \left[1 + \left(\beta_c \cos \theta_o (1 - n^{-2})^{1/2} - \sin \theta_o (1 - \beta_c^2)^{1/2} \right) / (1 - M^2)^{1/2} \right], \quad (2.26)$$

where all square roots are taken so that their real parts are nonnegative.

The values for the direct and reflected ranges (R_1 and R_2) are assigned from the direct and reflected arclengths of the rays calculated from the ray module. There are cases where there are no direct or reflected waves reaching the receiver known as a shadow

zone, see figure 2.3. Under these conditions, non-turbulent models will predict no sound will reach the receiver. It has been shown [7] that signals are still detectable in the shadow zone due to scattering from atmospheric turbulence. A qualitative model [8], figure 2.4, argues there are three regions present in an upward refractive atmosphere. Region I is outside of the shadow zone where typical propagation effects occur. Region II is the transition from the ensonified region, Region I, to the shadow zone region, Region III. Region III is in the shadow zone where the relative sound-pressure levels are down 20 to 30 dB beyond above their typical propagation levels. WSADA uses a value of 25 dB of additional attenuation over spreading losses within a shadow zone area.

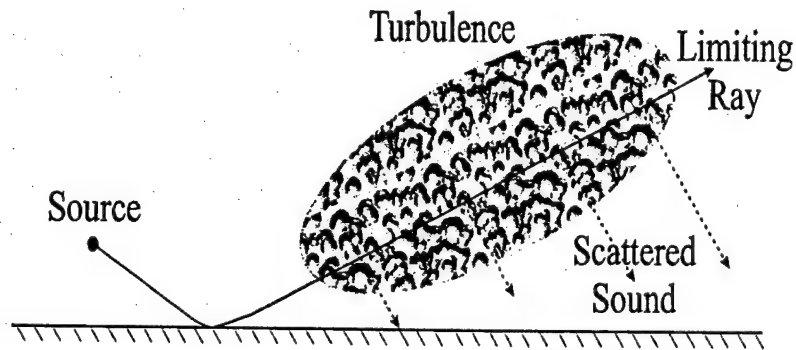


Figure 2.3: Shadow zone

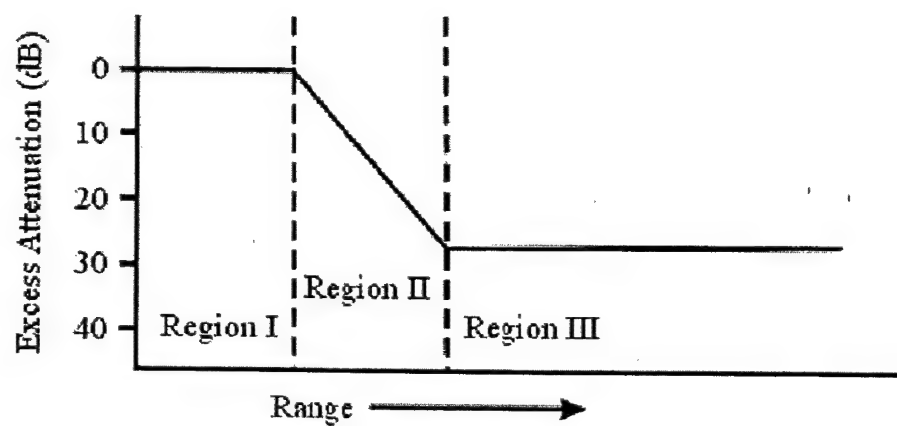


Figure 2.4: Attenuation of sound into a shadow zone

Chapter 3

Built-in Features

3.1 Output Smoothing

The attenuation of sound with range appear as a simple curve with range, or a very complex structure, depending on the number of paths in the atmosphere for the sound to reach the receiver, and also on the various modes of propagation present (surface wave, creeping wave, diffraction, etc.). Figure 3.1 shows an example of the complex structure of the attenuation of sound with range. When experiments are typically performed in the atmosphere, it is very difficult to measure the exact, complex structure. This is due to the fact that the atmosphere is dynamic. Atmospheric turbulence is constantly varying the temperature, wind speed, and wind direction. This results in continually changing fine structure in the attenuation curve. However, since acoustic sensor systems record a time average of the signal, much of the changing fine structure will average out. This is the reason for adding the output smoothing. The model performs an 11-point average on the attenuation of sound with range. This acts as a low-pass filter to average out the high frequency variations in the output. This technique provides for a much cleaner graph of the results of the calculation. Figure 3.2

shows the same case as figure 3.1 except with smoothing turned on. There is an option available to switch the smoothing off if one is interested in noting the difference it makes in the quality of the output graph. Future versions of our models that will include turbulence will be able to provide additional information on the bounds of the amplitude fluctuations and the bearing errors.

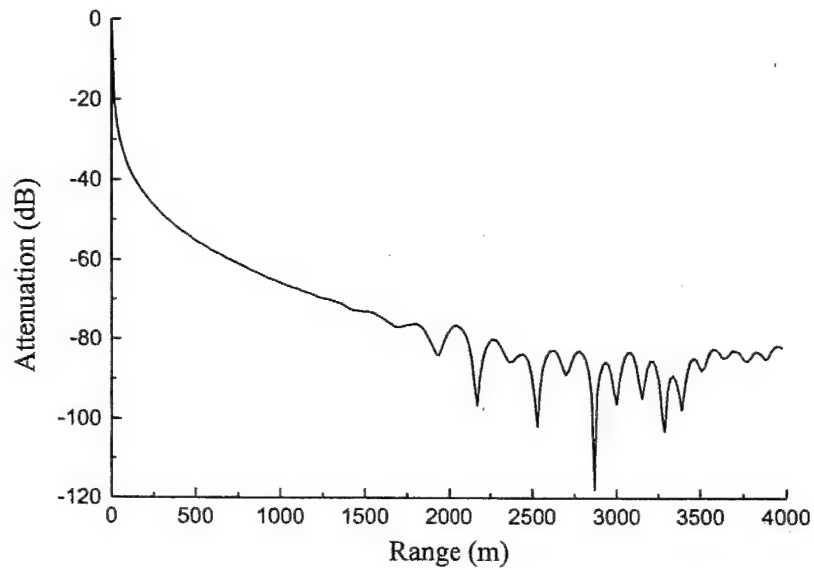


Figure 3.1: Attenuation with range without smoothing

3.2 Meteorological Profile Builder

Since the atmosphere plays a significant role in affecting the propagation of sound, knowing the state of the atmosphere is critical in performing a model calculation. Since users may not have meteorological profiles available to them for every location, a meteorological profile builder was developed to give the user a tool to create their own

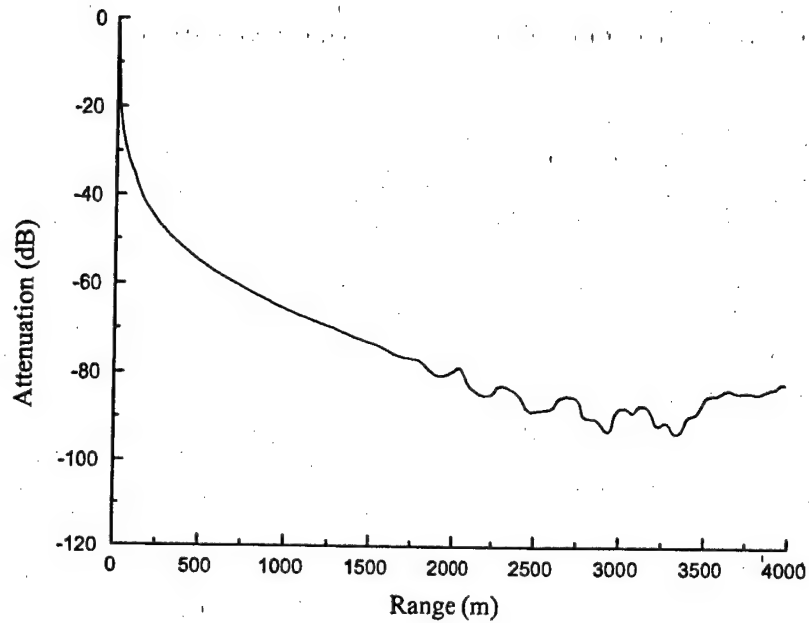


Figure 3.2: Attenuation with range with smoothing enabled

profiles based on basic information. The profile builder is not sufficient to generate profiles for calculations at large distances (> 5 km). This is due to the assumptions, which the profile builder is based on. For long-range propagation calculations, a more dynamic meteorological profile model must be used.

In the surface layer, mechanical and thermal forcing are the primary driving forces. Monin Obukhov introduced scaling parameters, which allowed the state-of-the-atmosphere to be described as functions independent of height. The scaling parameters are the friction velocity (u_*), scaling temperature (T_*), and the scaling length (L) with a normalized height $\zeta = z/L$. The temperature and wind speed profiles are calculated using [9]

$$u(z) = \frac{u_*}{k} \left[\ln \left(\frac{z}{z_o} \right) - \Psi_M(z/L) + \Psi_M(z_o/L) \right] \quad (3.1)$$

$$T(z) = T(z_t) + \frac{T_* P_t}{k} \left[\ln \left(\frac{z}{z_t} \right) - \Psi_H(z/L) + \Psi_H(z_t/L) \right] \quad (3.2)$$

where k is the von Karman's constant (0.4), z_o is the aerodynamic roughness length, z_t is an arbitrary height, and $P_t = 0.74$. The universal functions used in this development are

$$\Psi_M(\zeta) = \Psi_H(\zeta) = \frac{3}{2} \ln \left(\frac{1 - \phi^{-1} + \phi^{-2}}{3} \right) + \sqrt{3} \tan^{-1} \left(\frac{2\phi + 1}{\sqrt{3}} \right), \quad \zeta < 0 \quad (3.3)$$

$$\Psi_M(\zeta) = \Psi_H(\zeta)/p_T = -4.7\zeta, \quad \zeta > 0 \quad (3.4)$$

where

$$\phi_M(\zeta) = \begin{cases} (1 - 15\zeta)^{-1/3} & \zeta < 0 \\ 1 + 4.7\zeta & \zeta > 0 \end{cases} \quad (3.5)$$

$$\phi_H(\zeta) = \begin{cases} (1 - 9\zeta)^{-1/3} & \zeta < 0 \\ 1 + (4.7/P_t)\zeta & \zeta > 0 \end{cases} \quad (3.6)$$

The problem is what are good values for the friction velocity, scaling temperature, and scaling length for different locations, time-of-day, and seasons-of-the-year. In order to determine these parameters, the energy balance model developed by Rachele and Tunick [10] was employed. The model balances the energy flux at the soil surfaces as

$$R_N = H + L'E + G \quad (3.7)$$

where R_N is the net radiative flux, H is the turbulent sensible heat flux, $L'E$ is the

latent heat flux due to surface evaporation, and G is the flux of heat into the soil. Each term in the equation reduces to the basic measurable quantities. R_N can be expressed as the sum of the fluxes of the net shortwave and net longwave radiation. The energy balance model is constrained to require a minimum number of conventional meteorological inputs from a 2m-reference level. The inputs include temperature, pressure, relative humidity, and wind speed. The model also requires a judgment of the soil type and moisture, cloud characteristics, day-of-the-year, time-of-day, and longitude and latitude of the site of interest. Nearly all of these inputs are measured for most areas of the world and charts are available to estimate the soil characteristics. Appendix B provides the user a series of tables to choose some of the parameters that cannot be directly measured such as albedo, soil characteristics, etc. Using these inputs, the energy balance model calculates the similarity parameters required to calculate the temperature and wind speed profile required by the acoustic propagation model.

3.3 Run Options

WSADA offers the user the ability to set program flags that modify how certain calculations are made and generate additional output files. In the current version, there are several run options: source-to-receiver, receiver-to-source, output sound speed profile, disable smoothing, generate BASS output file, output ray information, and change the units of several of the meteorological inputs. The default configuration is for source-to-receiver, output sound speed profile, atmospheric pressure in millibars, wind direction in degrees, and temperature in celcius. Here is a description of each run option:

source-to-receiver: the sound is attenuated from the source to the receiver. This is used when the user wants to view the sound attenuation from a source (i.e. tank, helicopter, etc.)

receiver-to-source: the sound is attenuated from the receiver to the source. This is used when the user wants to view the sound attenuation from a sensor (i.e. WAM,

AHM, etc.)

output sound speed profile: allows the user to output the sound speed profile along the selected bearing for the given meteorological profile. This option generates one output file: sound.o. The file format for the output file is given below:

File Name: sound.o

Format:

Z(1) C(1)

Z(2) C(2)

⋮ ⋮

Z(Nint) C(Nint)

where Nint is the number of interfaces, Z(i) is the height of the ith interface in meters and C(i) is the sound speed of the ith interface in m/s.

disable smoothing: As discussed in Section 3.1, WSADA smoothes the higher frequency variations in the attenuation table. This option allows the user to switch the smoothing off if the case requires it.

output ray information: As part of the sound speed parser, a raytrace calculation is made to determine some characteristics of the atmosphere. The rays generated by the routine can be sent to a file named rays.out if the user would like to use this information.

pressure in millibars: The current version has changed the default units used for the atmospheric pressure. WSADA now defaults to use millibars as the measure of atmospheric pressure. To be compatible with older meteorological profiles, this flag was provided. If the user is using an older meteorological profile, which uses atmospheres as the measure of atmospheric pressure just unset this flag to correctly read the file. This change was made to better match the pressure units normally measured by met teams in the battlefield.

WSADA uses an array of flags to internally handle the run options. This array of flags can be seen in the configuration file. The first line in the configuration file is a printout of the flag array. In the current version, there is allocation for up to 16 run

flags, however, only eight flags are currently used. The remaining eight flags are for future use. A zero indicates the flag is off and a one indicates the flag is on. The order of the flags are: output sound speed profile, wind direction in degrees, source-to-receiver/receiver-to-source, reserved, reserved, reserved, reserved, disable smoothing, reserved, pressure in millibars, temperature in celcius, output ray information, output ray information, reserved, and reserved.

Chapter 4

Operations

4.1 Installing WSADA

4.2 How to Run WSADA

When the user runs WSADA, the program will display the window shown in figure 4.1. All of the user required information can be found under the "Model Inputs" menu. There are five selections to be made: meteorological profile, geometry, target frequency, ground characteristics, and run options. When the user runs the program, there is a default case that initializes the propagation model. The user can reset the program back to the run-time defaults by selecting the default settings. Appendix A will show the default settings.

The meteorological profile input gives the user three options to choose: open profile, use a standard meteorological case, and create a meteorological profile. The open profile is used when a meteorological profile is available. The format of the meteorological file is listed below:

Format:

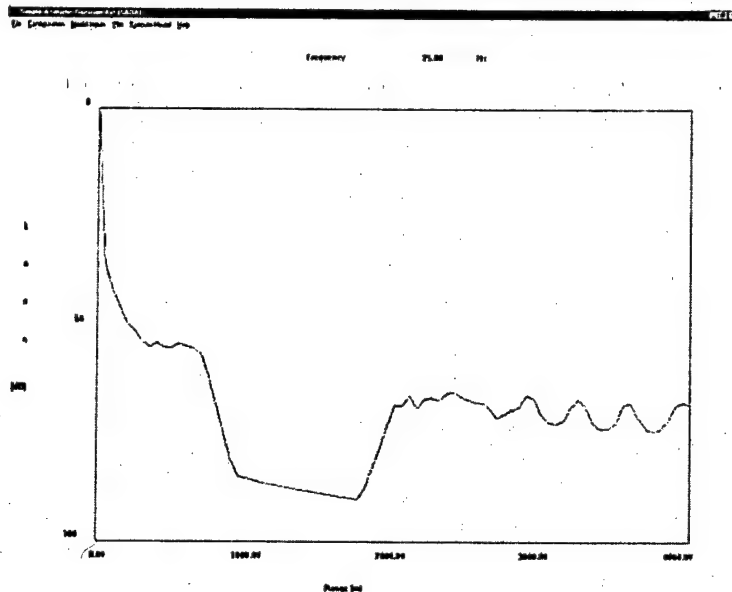


Figure 4.1: WSADA runtime window

Nint

| | | | | | |
|------|------|-------|------|---------|---------|
| Z(1) | T(1) | Rh(1) | P(1) | Wvel(1) | Wdir(1) |
| Z(2) | T(2) | Rh(2) | P(2) | Wvel(2) | Wdir(2) |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

Z(Nint) T(Nint) Rh(Nint) P(Nint) Wvel(Nint) Wdir(Nint)

where Nint is the number of interfaces, $Z(i)$ is the height of the i th interface in meters also $Z(1) = 0$ and $Z(i) < Z(i+1)$ always, $T(i)$ is the temperature in Kelvin, $Rh(i)$ is the relative humidity in percent, $P(i)$ is the atmospheric pressure in millibars, $Wvel(i)$ is the wind speed in meters per second, and $Wdir(i)$ is the wind direction in degrees, from which the wind is blowing relative to North. Each meteorological value is measured at height $Z(i)$. Choosing the open profile selection displays the open meteorological profile window as shown in figure 4.2. The selected profile will be read in and used to perform model calculations.

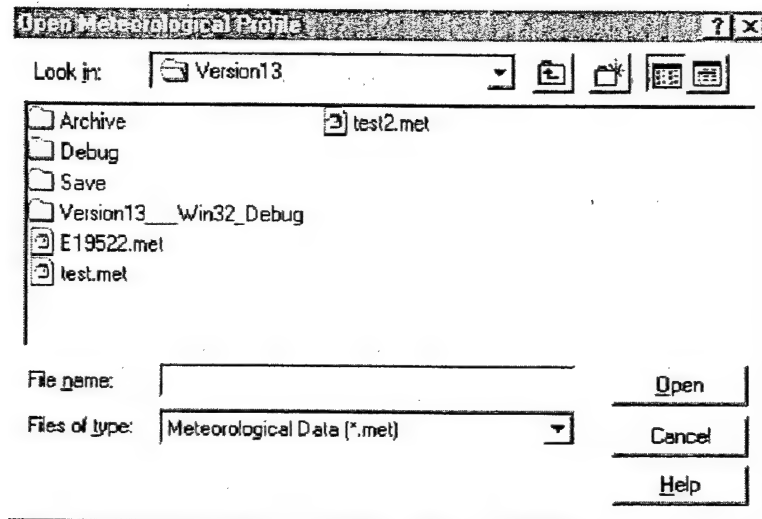


Figure 4.2: Open meteorological profile window

The next way of obtaining a meteorological profile is to select on the standard meteorological cases: overcast/calm, overcast/windy, sunny/calm, sunny/windy, night/calm, and night/windy, see figure 4.3. The six cases represent typical cases the user would observe. Once the user selects a standard case, they have to enter the temperature, relative humidity, and wind direction to complete the required inputs. If the user would like to further customize the values after pressing ok, select create a meteorological profile. The setting for the standard profile case will be copied to the create profile windows. For using the create profile windows, refer to Section 4.3. Selecting the ok button results in the creation of a meteorological profile.

Next, choose the target frequency and source level input selection. There are three choices to specify the frequency parameters (see figure 4.4): starting frequency, ending frequency, and frequency resolution. The starting frequency is the first frequency used in the frequency sweep. The ending frequency is the cutoff frequency for the sweep. The frequency resolution is the interval between frequencies in the sweep. The current

Choose a Standard Meteorological Case [X]

Choose one case

☐ Overcast, Calm ☐ Sunny, Windy
☐ Overcast, Windy ☐ Night, Calm
☒ Sunny, Calm ☐ Night, Windy

Temperature @ 2m deg C

Relative Humidity @ 2m %

Wind Direction @ 2m deg

OK Cancel

Figure 4.3: Standard meteorological profile window

version of WSADA does not allow for the frequency resolution to be 0. If the user wants to run one frequency, input the same value for the starting and ending frequencies and give a non-zero positive number for the resolution.

The next input selection is the ground characteristics. The options for this are shown in figure 4.5. WSADA gives the user several different types of grounds and ground conditions to choose from. The selection here will generate a value for the ground impedance used by the propagation model, see Section 2.4 for further information. A future version will allow the user to specify parameters for the ground impedance model.

The last input selection is the run options. The options for this are shown in figure 4.6. These input parameters allow the user to modify how the model runs and generate

| Set Frequency Range and Source Levels | |
|---------------------------------------|--|
| Starting Frequency (Hz) | Starting Source Level (dB re: 20 microPa) |
| 25.00 | 0.00 |
| Ending Frequency (Hz) | Ending Source Level (dB re: 20 microPa) |
| 250.00 | 0.00 |
| Frequency Resolution (Hz) | Background Noise Level (dB re: 20 microPa) |
| | 0.00 |
| OK | Cancel |

Figure 4.4: Frequency and source level window

additional output information. The details of the options and the default values are discussed in Section 3.3.

Once all of the inputs are given under the 5 sections, the user is now ready to run the propagation model to generate an attenuation table. To do this, select the execute model menu item. This will display a window to verify to the user if they are ready to perform a calculation and ask the user whether or not to continue. If the user presses the yes button, the propagation model will execute. The length of time to perform a calculation varies depending on the height of the meteorological profile, number of interfaces in the profile, number of frequencies, frequency values, and propagation range. The current version of WSADA may slow down or lock the windows until the calculations are complete. Future versions will provide a indication the program is still executing.

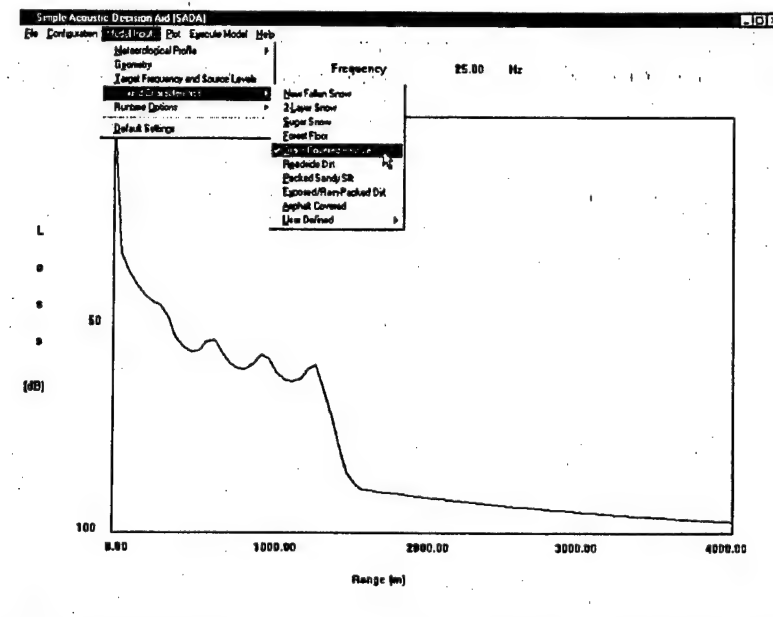


Figure 4.5: Ground characteristics menu

4.3 How to Run Meteorological Profile Builder

The meteorological profile builder is divided into two parts: basic and advanced. The basic window, figure 4.7, is what appears to the user when they select the create a meteorological profile option from the model inputs/meteorological profile menu. This window contains the minimal information the user must give the profile builder. The longitude, latitude, time-of-day, and day-of-the-year are used to calculate the solar angle. The solar angle and cloud cover determine the amount of solar radiation reaching the ground. The remaining four parameters go into determining the meteorological parameters used to generate the meteorological profile. The basic profile calculation assumes the location is at sea level, the ground is covered with low grass, and the soil is moist.

To alter these assumptions, the user must select the advanced button on the build a

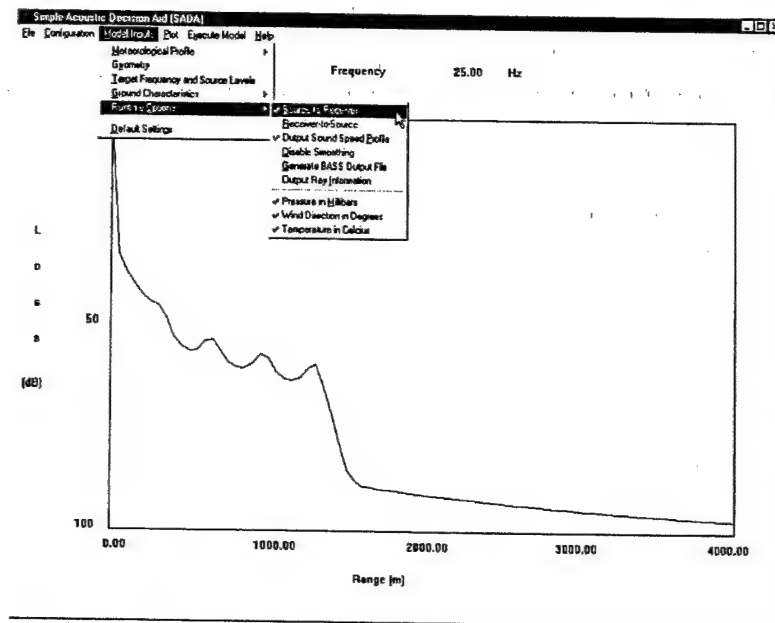


Figure 4.6: Runtime options menu

meteorological profile window. This creates another window shown in figure 4.8. This window contains additional parameters the user can use to customize the meteorological profile. Most of the parameters on this window require the user to have advanced knowledge about the environment. To aid the user in selecting values for this window, a series of tables have been provided in Appendix B. The tables will allow the user to select the values required to customize the profile builder to their scenario. Once all of the parameters have been entered, the user generates the profile by selection the ok button in each of the profile builder windows.

The generated profile is not automatically saved to a file. It resides in memory by default. It is recommended that the user uses the save option under the model inputs/meteorological profile/create a meteorological profile to store the profile to a file for later use. This way the user will not lose the profile in case the program abnormally terminates. If the user wishes to use the profile in the future, they just have to read the

Build a Meteorological Profile

| | | | | |
|---|--|--|--|---|
| Longitude <input checked="" type="radio"/> 25.0 deg <input type="radio"/> 0 deg <input type="radio"/> 90 deg <input type="radio"/> 180 deg <input type="radio"/> 270 deg | Latitude <input checked="" type="radio"/> +30.0 deg <input type="radio"/> 90 deg <input type="radio"/> 60 deg <input type="radio"/> 30 deg <input type="radio"/> 0 deg <input type="radio"/> -30 deg | Time of Day <input checked="" type="radio"/> 1200 <input type="radio"/> Morning (0800) <input type="radio"/> Noon (1200) <input type="radio"/> Afternoon (1600) <input type="radio"/> Evening (2000) <input type="radio"/> Night (0200) | Cloud Cover <input checked="" type="radio"/> 25% <input type="radio"/> 0% <input type="radio"/> 25% <input type="radio"/> 50% <input type="radio"/> 75% <input type="radio"/> 100% | Day of the Year Month: <input type="text" value="4"/> Day: <input type="text" value="15"/> <input type="radio"/> Spring (April 15) <input type="radio"/> Summer (July 15) <input type="radio"/> Fall (October 15) <input type="radio"/> Winter (January 15) |
| Wind Speed @ 2m Height <input checked="" type="radio"/> 0.5 m/s <input type="radio"/> Calm (0 m/s) <input type="radio"/> Light (2 m/s) <input type="radio"/> Moderate (5 m/s) <input type="radio"/> High (10 m/s) | Wind Direction @ 2m Height <input checked="" type="radio"/> 0.0 deg <input type="radio"/> 0 deg (North) <input type="radio"/> 90 deg (East) <input type="radio"/> 180 deg (South) <input type="radio"/> 270 deg (West) | Temperature @ 2m Height <input checked="" type="radio"/> +20.0 deg C <input type="radio"/> -10 deg C <input type="radio"/> 0 deg C <input type="radio"/> 10 deg C <input type="radio"/> 20 deg C <input type="radio"/> 30 deg C | Relative Humidity @ 2m Height <input checked="" type="radio"/> 25.0 % <input type="radio"/> 0% <input type="radio"/> 25% <input type="radio"/> 50% <input type="radio"/> 75% <input type="radio"/> 100% | |

OK Cancel Advanced

Figure 4.7: Meteorological profile builder window

profile back into memory.

4.4 Additional Features

In addition to the features described so far, WSADA also offers the user some additional capabilities: store/retrieve/view configurations, save/retrieve attenuation table, and print attenuation plots to a laser printer. The program has been tested on most types of HP compatible laserjet and inkjet printers.

In order to preserve the user's settings, WSADA allows the user to save the current input configuration into a file. Under the configuration menu, there are three options: open, save, and view. Open allows the user to open and read a previously stored configuration file. Save will store the current configuration into a file. The view option allows the user to see the values selected for the propagation model, see figure 4.9. The configuration file is ASCII with the format:

Format:

Advanced Meteorological Build

| Inversion (Cloud) Height | Surface Albedo | Roughness Height | Altitude Above Sea Level |
|---|-----------------------------|---|------------------------------|
| 1000.0 m | 25 % | 0.020000 m | 0.0 m |
| <input type="radio"/> 100 m | <input type="radio"/> 0 % | <input type="radio"/> Smooth (0.0002 m) | <input type="radio"/> 0 m |
| <input type="radio"/> 500 m | <input type="radio"/> 25 % | <input type="radio"/> Snow (0.002 m) | <input type="radio"/> 300 m |
| <input checked="" type="radio"/> 1000 m | <input type="radio"/> 50 % | <input type="radio"/> Low Grass (0.02 m) | <input type="radio"/> 600 m |
| <input type="radio"/> 2000 m | <input type="radio"/> 75 % | <input type="radio"/> Long Grass (0.05 m) | <input type="radio"/> 900 m |
| | <input type="radio"/> 100 % | <input type="radio"/> Trees (1.2 m) | <input type="radio"/> 1200 m |
| | | <input type="radio"/> City (1 m) | <input type="radio"/> 1500 m |
| | | | <input type="radio"/> 1800 m |

| | | | |
|---------------------------|---------------------------------------|-----------------------------|-----------------------------------|
| Surface IR Emissivity | <input type="text" value="0.98"/> | Soil Water Fraction | <input type="text" value="0.28"/> |
| Soil Thermal Diffusivity | <input type="text" value="0.001860"/> | Soil Porosity | <input type="text" value="0.50"/> |
| Soil Thermal Conductivity | <input type="text" value="0.44"/> | Cloud Shortwave Attenuation | <input type="text" value="90.0"/> |

Figure 4.8: Advanced meteorological profile builder window

```
// Configuration File for WSADA v1.3

// Run Options

options

// Geometry

// Source Height (m) Receiver Height (m) Bearing (deg)

Zsrc Zdet θ

// Range (m) Range Resolution(m)

R ΔR

// Frequency

// Start Freq (Hz) Stop Freq (Hz) Freq Resolution (Hz) //

f1 f2 Δf

// Start Level (dB) Stop Level (dB) Background Level (dB) //

dB1 dB2 backgnd

// Ground
```

// Number of Layers Layer Depth (m)

N_{gnd} d_{gnd}

// Sigma1 Sf1 Pn1 Omega1

σ_1 sf_1 Pn_1 Ω_1

// Sigma2 Sf2 Pn2 Omega2

σ_2 sf_2 Pn_2 Ω_2

// Ground Flag

gndflag

// Meteorology

// Meteorological Profile Options

metflag1

metflag2

// Size of File Buffer

buffer

// Name of Meteorological Profile

metname

// Plot Title

title

where run options are the 16 binary flags defining what options have been set. See Section 3.3 for a list of the options, Z_{src} is the height of the target in meters, Z_{del} is the height of the detector in meters, θ is the bearing in degrees, R is the maximum range of interest in meters, ΔR is the range step in meters, f_1 is the starting frequency in hertz, f_2 is the ending frequency in hertz, Δf is the frequency steps in hertz, dB_1 is the starting source level at frequency f_1 in decibels, dB_2 is the ending source level at frequency f_2 in decibels, $backgnd$ is background noise level in decibels, N_{gnd} is the number of ground layers (0 or 1), d_{gnd} is the depth of the top layer in meters, σ_1 is the flow resistivity in cgs units of the top layer, sf_1 is the pore shape factor of

the top layer, Pn_1 is the grain shape factor of the top layer, Ω_1 is the porosity of the top layer, σ_2 is the flow resistivity in cgs units of the bottom layer, sf_2 is the pore shape factor of the bottom layer, Pn_2 is the grain shape factor of the bottom layer, Ω_2 is the porosity of the bottom layer, gndflag is the type of ground surface used in calculation, metflag1 is the meteorological profile option selected, metflag2 is the flag indicating the meteorological profile was read from a file, and metname is the name of the meteorological profile used for the calculation. If the profile was generated by the profile builder, this field will be blank.

The screenshot shows a 'Configuration' window with the following sections:

- Geometry:**
 - Source Height: 5.00 m
 - Receiver Height: 1.00 m
 - Bearing: 0.00 deg
 - Range: 4000.00 m
 - Range Resolution: 50.00 m
- Configuration Parameters:**
 - Ground Conditions:**
 - # of Layers: 1
 - Layer Depth: 0.00 m
 - Sigma #1: 330.00
 - Sigma #2: 0.00
 - Sf #1: 0.88
 - Sf #2: 0.00
 - Pn #1: 0.75
 - Pn #2: 0.00
 - Omega #1: 0.68
 - Omega #2: 0.00
- Frequency:**
 - Starting Frequency: 25.00 Hz
 - Ending Frequency: 250.00 Hz
 - Frequency Resolution: 25.00 Hz
 - Starting Source Level: 0.00 dB
 - Ending Source Level: 0.00 dB
 - Background Level: 0.00 dB
- Runtime Options:**
 - Save Sound Speed Profile: ☐
 - Wind Direction in Degrees: ☐
 - Target to Sensor: ☐
 - Pressure in Millibars: ☐
 - Temperature in Celsius: ☐
- Meteorology:**
 - Name of Met Profile:

An 'Ok' button is located at the bottom center of the window.

Figure 4.9: Configuration view window

4.5 Format of Output Files

There are two output files produced by the program. The first is the attenuation table called proptab.ptd that is an ASCII table with a format of:

Format:

| | | | | |
|------|---------|---------|-----|---------|
| 0 | freq(1) | freq(2) | ... | freq(M) |
| R(1) | dB(1,1) | dB(2,1) | ... | dB(M,1) |
| R(2) | dB(2,1) | dB(2,2) | ... | dB(M,2) |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| R(N) | dB(1,N) | dB(2,N) | ... | dB(M,N) |

where N is the number of range points, M is the number of frequencies, and dB(j,i) is the relative sound level at the ith range and jth frequency in decibels (re: 20 μ Pa).

The other output file is a header file called proptab.pth providing information about the attenuation table. The format of the header file is:

Format:

```
// Propagation Table Header
//
// Created by WSADA v1.3
//
// ID String
Generated by WSADA v1.3
// Prop Data Table name
proptab
// Prop direction re wind
propdir
// Number of ranges (rows) in prop table
nranges
// Number of frequencies (columns) in prop table
nfreqs
// Atmospheric Conditions File
none
// c(z) data table
none
```

```
// Number of heights (rows in c(z) table
```

```
0
```

```
// Zmax (0 if unknown)
```

```
0
```

where proptab is the name of the file containing the propagation table with the extension .ptd, proptdir is the propagation direction relative to the wind in degrees, nranges is the number of ranges, and nfreqs is the number of frequencies. The remaining four fields are not implemented in the current version of WSADA. The default names for the attenuation table and header are proptab.ptd and proptab.pth, respectively.

Chapter 5

Future Revisions

The current version of SADA contains several limitations. The first limitation is on the number of rays found and stored for use in the hybrid calculations. The ray model only stores the first pair of direct and reflected rays found in a scan. In downward refractive cases, it is very likely several direct and/or reflected paths will reach the sensor. The next version will incorporate a ray model that scans for multiple ray paths from source-to-sensor. Next, the model will rank the found ray paths according to their contributions to the impact on the attenuation and select the rays that will have significant contributions to the overall attenuation. This will improve the levels predicted by the model. Another improvement is the number of reflections allowed. Currently the model only allows for one reflection between the source and sensor. If multiple reflections are possible, the ray and hybrid models must be modified to account for this scenario. This occurs for ducting conditions (nocturnal inversions or low-level jets) and long ranges. Also, the source representation will be improved to allow the user to define a more representative source. Finally, SADA will be integrated into the Acoustic Battlefield Aid (ABFA) [11] as part of the available suite of models. This will allow for a more detailed source definition and link the model to a terrain display.

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Appendix A

Example Case

This appendix provides an example case against which the user can compare their version of the code. This aids in determining whether the code was installed correctly and training for the new user. The meteorological data and configuration files for the case were provided with the program code. The example case will also be used to illustrate some of the environmental effects on sound propagation. Since the meteorological data file will be provided with the program, tabulation of the input data will not appear in this appendix as in previous user manuals.

For this case, the meteorological profiles of temperature, wind speed, and wind direction are shown in figures A.1 – A.3, respectively. This surface wind is light from the northeast. There is a low-level wind jet (local maximum in the wind speed) at 100 m and the wind direction from the northwest. The effect of this low-level wind jet will be obvious when the sound speed profile is examined. As can be seen in the wind speed profile, there is a shift in the wind direction at the top of the temperature inversion from the north to the southeast. Figure A.4 shows the sound speed profile in 2 directions: North and East. This represents propagation upwind and crosswind.

The sound speed profile provides a wealth of information. Looking at the sound

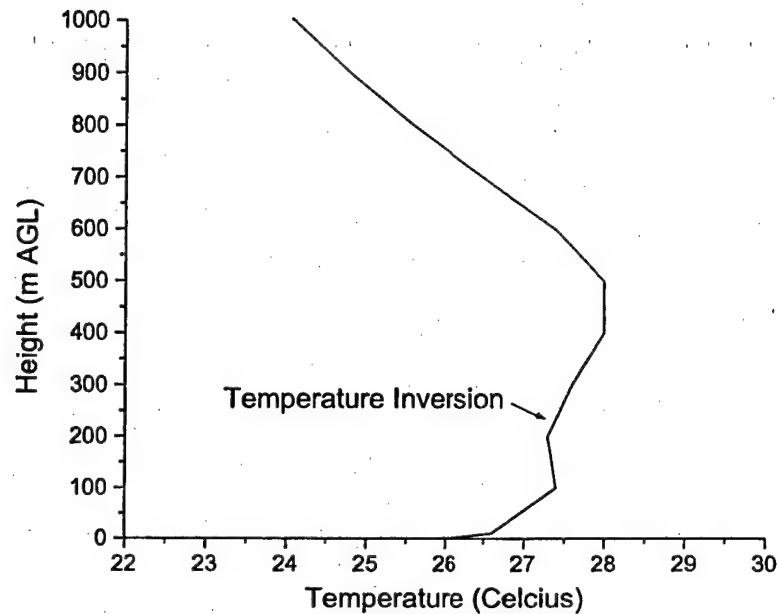


Figure A.1: Temperature profile.

speed profile to the north (0 degrees), the sound speed is decreasing with height indicating upward refraction thus poor propagation conditions. This condition extends to the middle of the wind jet at 100 m. The upper half of the wind jet (100 – 250m) caused a downward refraction region as indicated by the increasing sound speed with height. This means that the sound will initially be refracted up away from the ground causing rapid increase in the attenuation of sound with range until the acoustic wave reaches 100 m AGL. Above this height, the acoustic wave will be refracted back towards the ground forming an acoustic duct. This means that at a set range, the acoustic wave will reach the ground and reflect back up resulting in a large decrease in the attenuation field. Looking to the east, the first 100 m are now downward refractive instead of upward. This means that the attenuation in this direction is not as great as it was to the

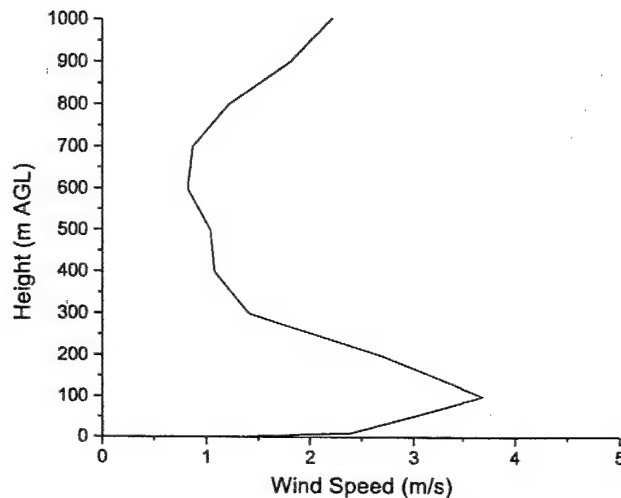


Figure A.2: Wind speed profile

north.

The attenuation plots in figures A.5 and A.8 were configured for a case of a helicopter flying 30 m AGL with a ground sensor 0.33 m from the ground. This simulates an anti-helicopter mine. The attenuation to the north of the helicopter shows a rapid increase until the refracted wave returns and is reflected at 7.5 km. Applying the source and background levels, figures A.6 and A.7 shows the SNR for the helicopter at 15 and 45 Hz. In this simple sensor model, SNR levels above 0 dB indicates a detection and levels below 0 dB indicates no detection. The 15 Hz signal is detectable until about 2-3 km from the helicopter. A sensor will not detect the helicopter from 3-7 km. The sensor will acquire the target from 7-17 km with a possible temporary loss about 14 km. The 45 Hz signal is only detectable until 1.5 to 2 km from the target. The level does rise high enough for the sensor to possibly detect the target at about 9 km distance.

Figures A.9 and A.10 shows the SNR for the helicopter at 15 and 45 Hz for propagation to the east. The 15 Hz signal is detectable with several dB of signal remaining

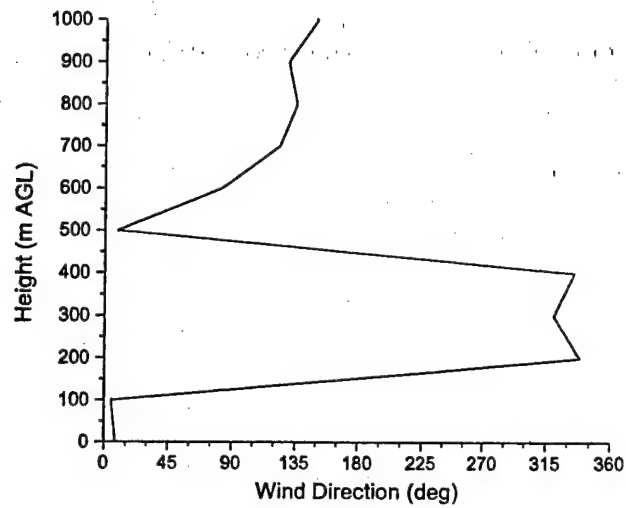


Figure A.3: Wind direction profile

20 km from the target. The 45 Hz signal is detectable until about 8 km from the target.

The sensor may temporarily drop the target at about 2 km.

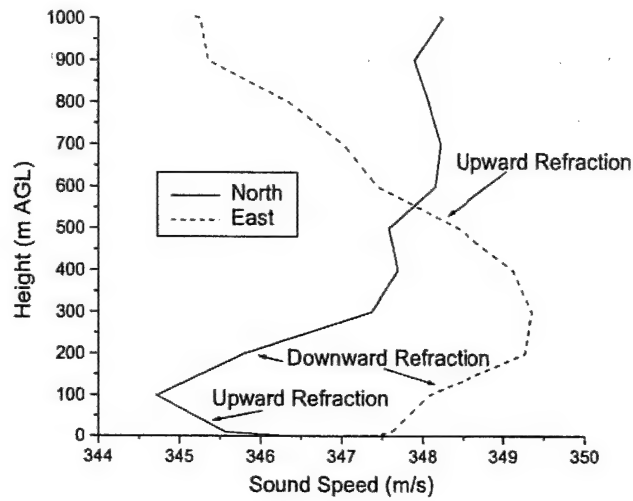


Figure A.4: Sound speed profile to the north and east of the target.

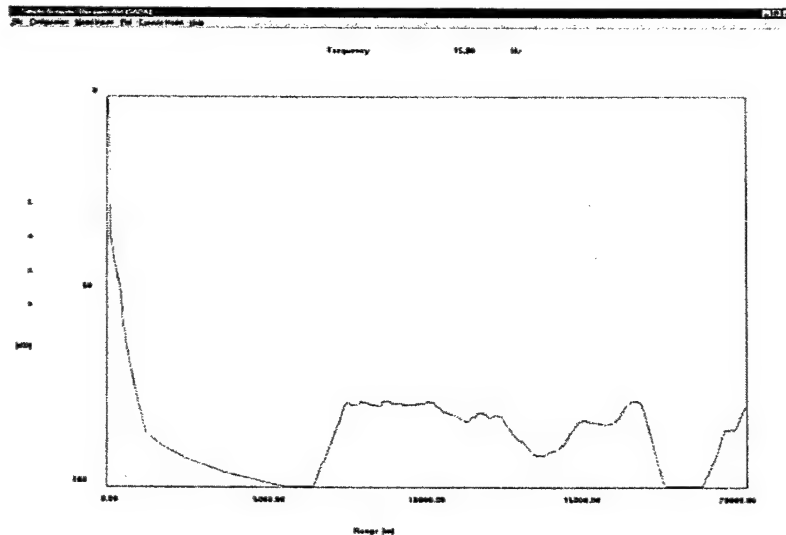


Figure A.5: Attenuation with range to the north of the target for 15 Hz.

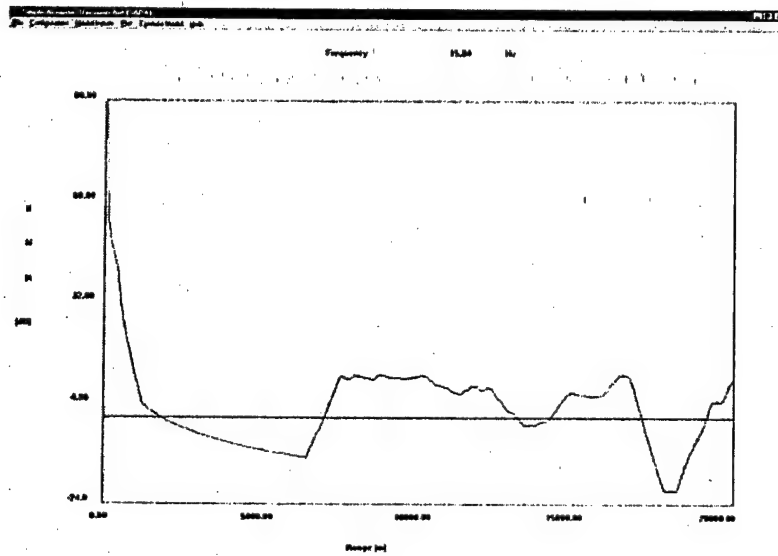


Figure A.6: Signal-to-noise ratio with range to the north of the target for 15 Hz.

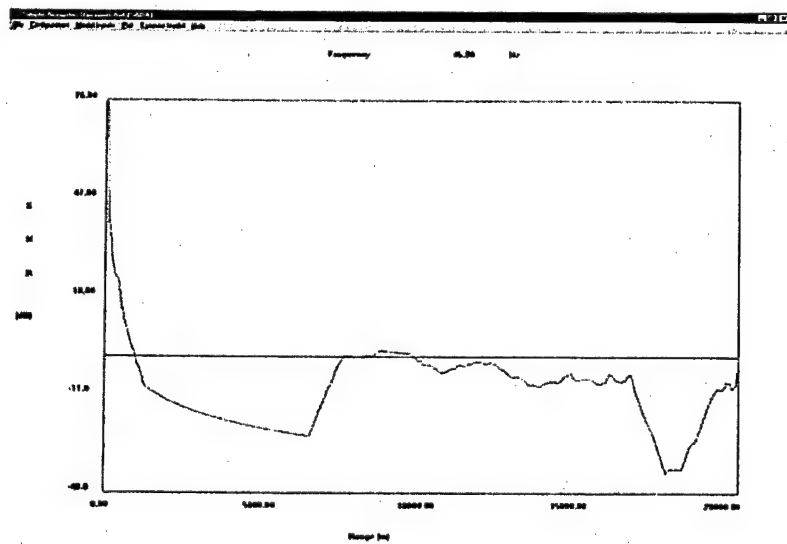


Figure A.7: Signal-to-noise ratio with range to the north of the target for 45 Hz.

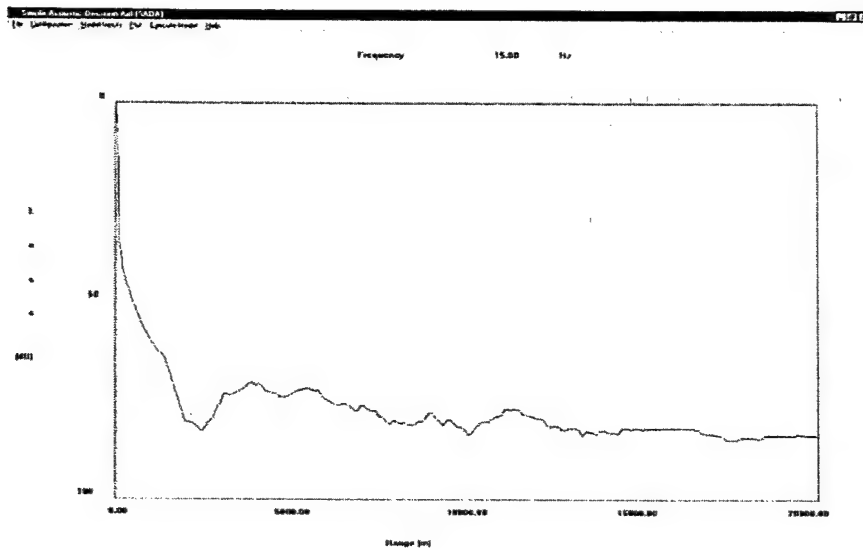


Figure A.8: Attenuation with range to the east of the target for 15 Hz.

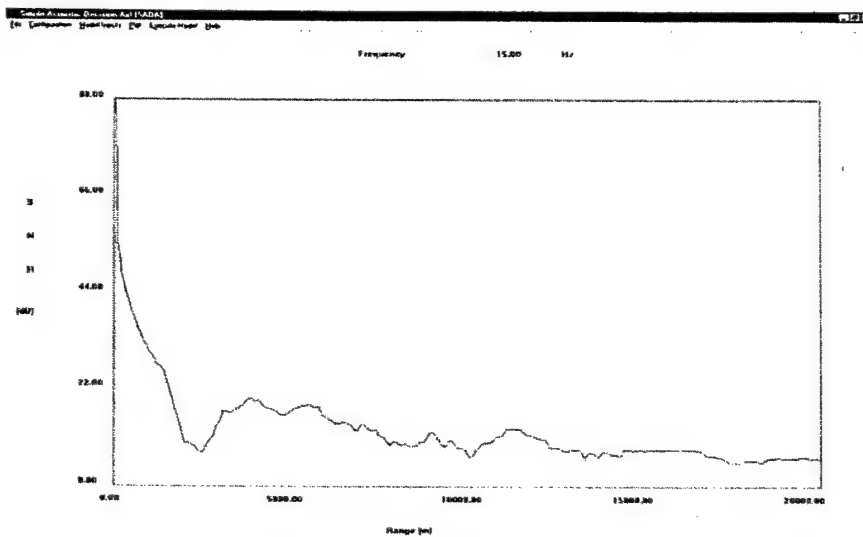


Figure A.9: Signal-to-noise ratio with range to the east of the target for 15 Hz.

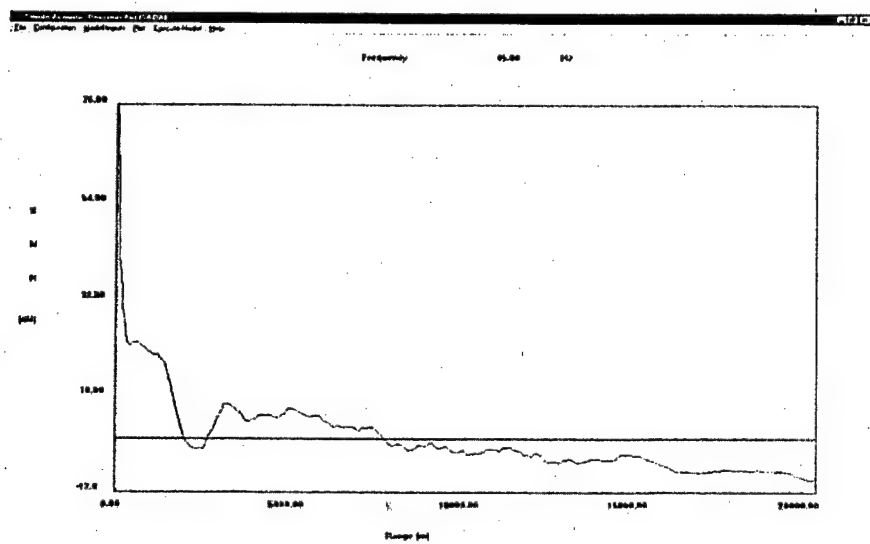


Figure A.10: Signal-to-noise ratio with range to the east of the target for 45 Hz.

Appendix B

Meteorological Profile Builder

Lookup Tables

Table B.1: IR Emissivity

| Ground Cover | ϵ |
|----------------------|-------------|
| Fresh snow | 0.99 |
| Old snow | 0.82 |
| Dry sand | 0.95 |
| Wet sand | 0.98 |
| Dry peat | 0.97 |
| Wet peat | 0.98 |
| Soils | 0.9 – 0.98 |
| Asphalt | 0.95 |
| Concrete | 0.71 – 0.9 |
| Tar and gravel | 0.92 |
| Limestone gravel | 0.92 |
| Light sandstone rock | 0.98 |
| Desert | 0.84 – 0.91 |
| Grass lawn | 0.97 |
| Grass | 0.90 – 0.95 |
| Deciduous forests | 0.95 |
| Coniferous forests | 0.97 |
| Urban area (range) | 0.85 – 0.95 |

Table B.2: Surface Albedo

| Surface | α | Surface | α |
|----------------------------------|----------|--|----------|
| Snow and Ice | | Urban (people influenced) | |
| Snow, fresh fallen | 75 – 95 | Road, black top | 14 |
| Snow, thawing | 20 – 65 | Road, stone | 15 |
| Snow, old | 40 – 70 | Road, dirt, wet | 18 |
| Snow, icy | 75 | Road, dirt, dry | 35 |
| Ice, grey | 60 | Road, clay, wet | 20 |
| Ice, white | 75 | Road, clay, dry | |
| Ice, water covered | 26 | Road, asphalt, wet | 10 |
| Ice, light snow cover | 31 | Road, asphalt, dry | 15 |
| Ice, porous and melting | 41 | Parking lot, black top | 8 |
| Desert shrublands, snow covered | 18 – 19 | Concrete, new, white | 37 |
| Conifer forest, snow covered | 59 – 67 | Buildings | 9 |
| Mixed forest, 50 cm snow covered | 20 | Developed urban area (average) | 15 |
| Grasslands, snow covered | 46 – 50 | Roof, thatched, new | 20 |
| Crops, snow covered | 18 – 19 | Roof, thatched, old | 15 |
| Tundra, snow covered | 59 – 67 | Roof, tiled, dirty | 8 |
| Soil and Rocks | | Crops, Natural Terrain, and Vegetation | |
| Soil, dark, wet | 8 | Fallow field, wet | 5 – 7 |
| Soil, dark, dry | 13 | Fallow field, dry | 8 – 12 |
| Soil, light, wet | 10 | Spring wheat | 10 – 25 |
| Soil, light, dry | 18 | Winter wheat | 16 – 23 |
| Dark organic soils | 10 | Rice paddy | 12 |
| Dark gray silt | 12 | Winter rye | 18 – 23 |
| Red soils | 17 | Forest, coniferous | 5 – 15 |
| Clay, wet | 16 | Forest, deciduous | 10 – 20 |
| Clay, dry | 23 | Grass, green | 26 |
| Clay loam, wet | 19 | Meadows, green | 10 – 20 |
| Clay loam, dry | 13 | Coniferous trees, dormant | 12 |
| Lime | 45 | Deciduous trees, dormant | 12 |
| Gypsum | 55 | Tall grass, dormant | 13 |
| Sand, white, wet | 25 | Mowed grass, dormant | 19 |
| Sand, white, dry | 35 | Tundra | 15 – 20 |

Table B.3: Thermal Properties of Soils

| Material | State | Soil Thermal Conductivity ($\times W m^{-1} \times K^{-1}$) | Soil Thermal Diffusivity ($\times m^2 \times h^{-1}$) |
|-----------------|------------|--|--|
| Sand | Dry | 0.277 | 0.000900 |
| Sand | Moist | 2.0 | 0.002520 |
| Sand | Saturated | 2.2 | 0.002120 |
| Quartz sand | Dry | 0.264 | 0.000720 |
| Quartz sand | 8.3% moist | 0.586 | 0.001188 |
| Yolo silt loam | Dry | 0.12 | 0.000450 |
| Yolo silt loam | Moist | 0.44 | 0.001860 |
| Yolo silt loam | Saturated | 0.848 | 0.001730 |
| Sandy loam | Dry | 0.23 | 0.000576 |
| Sandy soil | Saturated | 2.2 | 0.002660 |
| Sandy clay | 15% moist | 0.925 | 0.001330 |
| Clay soil | Dry | 0.3 | 0.000549 |
| Clay soil | Moist | 1.47 | 0.003960 |
| Clay soil | Saturated | 1.58 | 0.001840 |
| Clay pasture | — | 2.76 | 0.004320 |
| Calcareous soil | 43% moist | 0.712 | 0.000648 |
| Soil (generic) | Very dry | 0.167 – 0.345 | 0.00072 – 0.0011 |
| Soil (generic) | Wet | 1.26 – 3.35 | 0.000144 – 0.00036 |
| Mud | — | 0.84 | 0.000792 |
| Peat soil | Dry | 0.13 | 0.000540 |
| Peat soil | Saturated | 0.85 | 0.000432 |

Table B.4: Roughness Length for Different Surfaces

| Type of Surface | z_o (m) |
|--|---------------|
| Ice / Smooth mudflats | 0.00001 |
| Dry lake bed | 0.00003 |
| Tundra, snow covered | 0.0001 |
| Tundra, patchy snow | 0.0003 |
| Calm open sea | 0.0001 |
| Desert, smooth | 0.0003 |
| Farmland, snow covered | 0.002 |
| Bare soil, tilled | 0.002 – 0.006 |
| Prairie | 0.01 |
| Grass and trees, mixed | 0.035 |
| Brush, scrub growth, open | 0.16 |
| Brush, scrub growth, dense | 0.25 |
| Forested plateau, level topography | 0.7 – 1.2 |
| Forested plateau, rolling hills | 1.25 |
| Subtropical savanna, grass, few trees | 0.31 – 0.41 |
| Subtropical savanna, grass w/many shrubs | 0.51 – 0.61 |
| Coniferous forest | 1.1 |
| Residential, low density | 1.1 |
| City park | 1.3 |
| Urban, buildings, business district | 1.75 – 3.20 |